Aeolian dust in a saline playa environment, Nevada, U.S.A.

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Saline playas in north-western Nevada, U.S.A., remnants of pluvial periods of the Pleistocene, represent a tremendous source of unconsolidated sediments available for aeolian transport. This study investigated the transport of aqueous-soluble solutes in dust from July 1994 through June 1996 along a transect from a barren salt-encrusted playa surface (elevation = 1224 m), to a former pluvial lake beach (elevation = 1228 m), to a dune-mantled upland (elevation = 1248 m). The content of aqueous-soluble solutes in aeolian dust showed a significant ($p \leq 0.05$) interaction with dust trap location (playa, beach, dune) and time of collection. Dust collectors on the playa surface generally contained significantly more aqueous-soluble solutes and had greater total flux of solutes than either the beach or the dune locations. The solute content of aeolian dust was usually higher, in some cases several orders of magnitude, than that in the surface 5 cm of soil. Recent changes in playa hydrology may explain this result. Pulses of nitrate-rich dust, synchronous with spring emergence, and other nutrient additions via aeolian dust may have stimulated invasion of dune-mantled uplands by the weed *Salsola paulsenii* (barb-wire Russian thistle).

Introduction

The Great Basin section of the Basin and Range physiographic region of the western United States occupies over 500,000 km^2 in Nevada, southern Oregon, southern Idaho, western Utah, and California (Hunt, 1974). Early Miocene crustal extension created generally north-south trending arrays of mountains separated by basins (Stewart, 1980). These basins presently have no external drainage and during pluvial periods of the Pleistocene about 120 were occupied by lakes (Mifflin & Wheat, 1979). Lack of external drainage caused the lakes and subsequent dry lake beds to become saline due to evaporative concentration of solutes. Lake Lahontan in north-east Nevada occupied a hydrographic basin covering an area of 116,000 km^2; this pluvial lake consisted of many interconnected basins with a lake surface area of 22,000 km^2 (Russell, 1885). Lake Lahontan retreated to its individual basins during drier periods of the Pleistocene; only

structurally lower basins with appreciable water inflow remained as lakes (Morrison, 1991). The exposed unconsolidated saline sediments were, and are subject to wind erosion, and over time sent voluminous plumes of dust downwind which influenced pedogenesis and vegetation communities (Blackwelder, 1931; Billings, 1945; Morrison, 1964; Chadwick & Davis, 1990; Reheis, 1990).

Research was initiated upon the observation that a high ecological condition *Achnatherum* (*Oryzopsis*) *hymenoides* (Indian ricegrass) community adjacent to a Lake Lahontan playa was being invaded by *Salsola paulsenii* (barb-wire Russian thistle). Our working hypothesis postulated that aeolian dust originating from the playa surface was supplying nutrients, particularly nitrate, to the soil thereby stimulating the germination, rapid growth, and invasiveness of the weed. This paper reports on a 2-year study of solutes in aeolian dust in a saline playa environment.

Methods

Field

The study was conducted adjacent to Eagle Valley playa, in section 29, T21N, R26E (39°40′N, 119°5′W), located 80 km east of Reno, Nevada (Fig. 1). Eagle Valley is a small embayment of pluvial Lake Lahontan with an area about 70 km². It is bound to the north-west by the Truckee Range and to the south-east by the Hot Springs Mountains. During pluvial periods, the western boundary of the playa was the terminus of the Truckee river, a major river draining the Sierra Nevada range to the west of the study area. The elevation of the playa surface is 1224 m. At maximum lake levels during pluvial cycles of the Pleistocene (Morrison, 1964), water covered the playa to a depth of approximately 110 m. Presently, water ponds on the barren playa surface only during years of heavy runoff from adjacent slopes.

Measurements were made from July 1994 through June 1996. Precipitation the year preceding the study was near normal, but followed a drought lasting 5 years (Table 1). Beginning in January 1995, the area received greater than normal precipitation which, combined with heavy runoff from the surrounding mountains, resulted in greater and longer coverage of the playa by standing water. January, the coldest month, has an average maximum temperature of 7·2°C and an average minimum temperature of − 7·2°C. August, the hottest month, has an average high of 32·8°C and an average minimum of 11·8°C.

Our study area encompassed the south-central portion of Eagle Valley playa extending nearly 1 km east into an alluvial fan of the Hotsprings Mountains (Fig. 1). Three replicate aeolian dust collectors were placed on the soil surface at three locations. The first location was on the edge of the playa. The surface is salt-encrusted and silty clay loam to silty clay in texture. Underlying material within 20 cm is clay loam, sandy clay loam, and fine sandy loam in texture. The water-table is shallow, generally less than 40 cm. The surface is dotted by widely spaced (mean spacing 12 m) mounds averaging 2 m in diameter and 0·5 m in height occupied by *Allenrolfea occidentalis* (iodine bush [S. Watson] Kuntze) and *Sarcobatus vermiculatus* (black greasewood [Hook.] Torrey [L.] Greene). *Distichlis spicata* (saltgrass [L.] E. Greene) occupies the edges of some mounds extending as strings of clonal colonies into mound interspaces. The second location is on a former pluvial-lake beach ridge (elevation = 1228 m) approximately 270 m east of the playa location. The soil does not contain visible salt efflorescences. Soil textures of the upper 20 cm are silty clay loam, loam, and sandy loam. Basalt and andesite cobbles and boulders dot the landscape. The landscape is marked by low mounds (0·2–2 m in diameter with a height of between 0·1–0·3 m) spaced an average of 1 m apart, occupied by *Atriplex confertifolia* (shadscale [Torrey & Fremont] S. Watson), *Atriplex canescens* (fourwing saltbush [Pursh] Nutt.), *Psorothamnus polydenius* (dotted dalia [S. Watson] Rydb), and *Sarcobatus vermiculatus.* The third location is
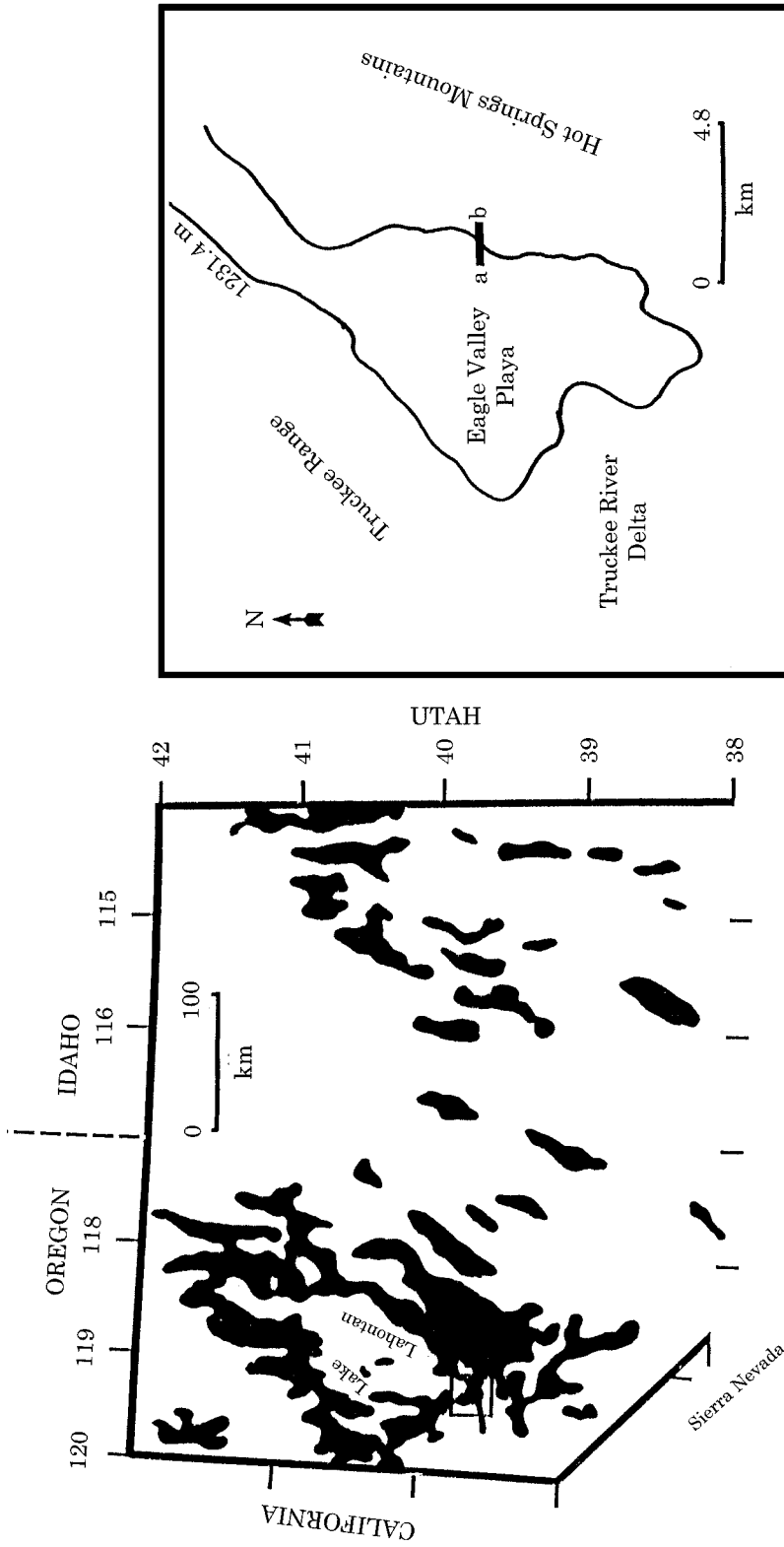
Figure 1. Map of northern Nevada showing the maximum extent of pluvial Lake Lahontan and other pluvial lakes during the late Pleistocene. The location of the study area in relation to surrounding mountains and the location of the dust collection transect (a–b) are shown in the enlarged panel.

Table 1. *Bimonthly precipitation (cm) at Fallon, NV (30 km south-east of the study site) before and during the study period. Long-term average yearly precipitation is 12·95 cm*

Year	Jan–Feb	Mar–Apr	May–Jun	Jul–Aug	Sep–Oct	Nov–Dec	Total year
1993	0·74	4·52	3·43	0·00	3·07	2·26	14·02
1994	1·57	2·00	4·09	0·38	0·43	4·83	13·30
1995	4·06	2·62	12·11	0·00	0·00	1·52	20·31
1996	1·38	1·50	4·78	0·86	0·51	1·91	10·94

a dune-mantled upland (elevation = 1248 m) 820 m east of the playa location. Soil textures are loamy sand and sandy loam. The site is occupied by *Achnatherum hymenoides* (Indian ricegrass [Roemer & Schultes] Barkworth), *Psorothamnus polydenius*, and *Atriplex confertifolia.* Beginning in 1990, *Salsola paulsenii* (barb-wire Russian thistle Litv.) has invaded the dune-mantled uplands.

Marble dust collectors were used to trap aeolian dust. Traps consisted of teflon-coated cake pans ($32 \times 23 \cdot 5 \times 5 \cdot 5$ cm deep). The pans were filled to a depth of 5 cm with 1·5-cm diameter glass marbles. Collectors were placed at the soil surface in plant interspace positions; the three replicates were in a line about 5 m apart.

Two protocols were used to sample the aeolian dust. If there was no evidence of precipitation during the collection period, dust was separated from the marbles by shaking for a period of 15–30 s through a sieve that retained the marbles. Dust adhering to the pans was brushed off and combined with dust collected through the sieve. The marbles were then replaced in the pans and collectors returned. If there was evidence that a precipitation event had occurred during the sampling period (water in pans or crusting of dust in bottom of pans) the marbles and pans were washed with deionized water until free of dust into large bottles. The washed marbles were returned to the clean pans for the next sampling period. At the time of each aeolian dust collection, a surface soil sample (0–5 cm) from each sampling location (playa, beach, dune) was taken near one of the dust collectors.

On 5 January 1998 soil samples (three replicates) were collected at the playa, beach, and dune sampling sites at depths of 0–5, 5–10, and 10–20 cm. These samples were taken at this time to gage the potential importance of dust infiltration into the soil profile.

Laboratory

All samples were dried at 105°C and the weight of dust recorded. Plant material was removed with tweezers and the samples were homogenized by crushing with a mortar and pestle. Aqueous-soluble solutes were determined by mixing a known weight of dust or soil with a known volume of deionized water and shaking for 1 h. After shaking, the samples were centrifuged and analysed. Ion chromatography was used to quantify chloride, nitrate, sulfate, sodium, and potassium. Ammonium was quantified using flow-injection, membrane diffusion methodology. The azomethine-H method was used to quantify boron (John *et al.*, 1975). Oxalate was determined on an HCl-acid-extract; the extract was obtained using approximately 0·2 g dust, 2 mL of 1 M HCl, and 10 mL of deionized water, and shaking for 1 h followed by centrifugation. Oxalate was quantified by ion chromatography. Fluxes of aqueous-soluble and acid-extractable solutes were determined by multiplying a particular solute concentration by dust weight and by a factor to convert dust collector area to m². Selected subsamples of aeolian dust were examined with a petrographic microscope to gage the relative proportion of minerals present.

The experimental design was a randomized complete block (blocked on year) with subsampling. The factors were time (Jan–Feb, Mar–Apr, May–Jun, Jul–Aug, Sep–Oct, and Nov–Dec) and location (playa, beach, dune). Data were analysed using a two-way ANOVA. For significant F-test values, Duncan's new multiple range test was used for mean separation. Because boron was measured for only one year, the data were analysed separately as a completely randomized design with time and location as factors. Correlation was used to indicate the degree of linear relationship among measured attributes for solute concentration and solute flux.

Results and discussion

Dust flux and water-soluble solutes

Extraordinarily high levels of aeolian dust accumulated in the beach and dune collectors during some periods, e.g. March–April 1995 (Fig. 2). In general, average dust flux increased from playa to dune. Microscopic inspection of dust samples showed that silt-sized halite crystals and diatomite aggregates (clumps of partially cemented diatom tests) constituted the majority of dust in the playa collectors. Silt- and sand-sized quartz, feldspars, and diatomite aggregates were the dominant components in beach and dune dust collectors. Aeolian dust collected at the playa site contain a high proportion of aqueous-soluble solutes, far more than the beach and dune collectors (Table 2).

The yearly aeolian dust flux found in this study of $21,000$ to $140,260$ kg ha^{-1} year^{-1} exceeds that of 65 to 250 kg ha^{-1} year^{-1} reported by Reheis & Kihl (1995) for southern Nevada. This difference in magnitude is largely due to the placement of the dust collectors. In their study, dust collectors were placed 2 m above-ground to avoid capture of saltating particles. By placing our dust collectors at the soil surface, a sizable proportion of captured particles were transported by saltation. This fact, in part, explains why dust flux was greatest in beach and dune locations; the sandy surface soil textures, combined with surface roughness, promulgate greater transport via saltation. Young & Evans (1986), who also placed dust collectors at the soil surface, reported a maximum dust deposition rate of 29,000 kg ha^{-1} year^{-1} along a playa margin in central Nevada. Offer *et al.* (1992) reported dust deposition rates at the soil surface
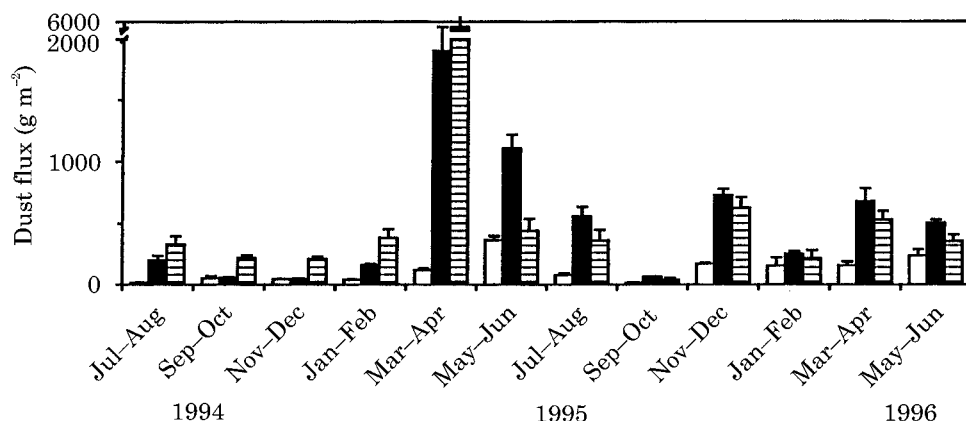

Figure 2. Bimonthly aeolian dust flux values (and standard error bars) during the study period by collection location: (□) = playa; (■) = beach; (▤) = dune. Yearly cumulative dust flux rates: playa = 21,000 kg ha^{-1} year^{-1}; beach = 93,980 kg ha^{-1} year^{-1}; dune = 140,260 kg ha^{-1} year^{-1}. ANOVA: time × location, $p < 0.0001$.

Table 2. *Per cent by weight of aqueous-soluble solutes * in aeolian dust and soil by location. Data were pooled over time and standard errors are shown in parentheses*

Location	Aeolian dust	Soil
Playa	44·20 (2·20)	9·36 (1·05)
Beach	0·46 (0·10)	0·12 (0·08)
Dune	0·15 (0·02)	0·01 (0·004)

* Data generated by summing per cent by weight of aqueous-soluble calcium, magnesium, sodium, chloride, sulfate, potassium, nitrate, and ammonium.

of between 1984 and 2760 kg ha^{-1} year^{-1}. The dust flux values obtained in this study exaggerate actual deposition rates because erosion from sites was not measured. The magnitude of aeolian dust movement in this environment, however, is staggering. Young & Evans (1986) speculated that vesicular surface soil horizons, formed via aeolian dust deposition largely from playas (Reheis *et al.*, 1995) may limit seedling establishment in downwind shrub interspaces.

Playa dust generally had a greater nitrate-N content than beach or dune dust (Fig. 3). In a trend repeated for most other measured solutes, nitrate-N content in dust far exceeds that in surface soil. For the beach and dune locations, nitrate-N content of dust generally decreased from 1994 to 1996. Concentration of nitrate-N in dust did not significantly correlate with the concentration of any other measured solutes. In the Negev Desert, Offer *et al.* (1992) reported nitrate-N content ranging from 3·0 to 11·0 mg kg^{-1}, which is considerably less than measured during some collection periods in this study. The yearly flux rate of nitrate-N in aeolian dust (Fig. 3) is similar to that reported by West (1978) for nitrate-N input from precipitation for locations in the Great Basin. Offer *et al.* (1992) reported nitrate-N fluxes between 0·012 and 0·013 kg ha^{-1} year^{-1}.

Ammonium-N dust content was highest in beach and dune locations (Fig. 4). Levels of ammonium-N rose, then declined significantly from 1994 to 1996. Offer *et al.* (1992) reported that the ammonium-N content of aeolian dust ranged from 2 to 15 mg kg^{-1} and ammonium-N flux between 0·008 and 0·02 kg ha^{-1} year^{-1}. Except for several sampling periods for the playa location, levels of ammonium-N in dust were far greater than that in the surface 5 cm of soil. Similar to nitrate-N, concentration of ammonium-N in dust and ammonium-N flux did not significantly correlate with any other measured solutes or fluxes.

Aeolian dust emanating from the playa contained high concentrations of sulfate (Fig. 5). Levels of sulfate in dust declined precipitously and significantly from the playa location to the beach and dune locations. The highest concentration of sulfate in dust occurred in the second year for the playa location and in the first year for the beach and dune locations. Sulfate concentration did not significantly correlate with concentrations of other measured solutes for the playa location, but correlated with chloride ($r^2 = 0.71$) for the beach location, and chloride ($r^2 = 0.86$) and sodium ($r^2 = 0.80$) for the dune location. Sulfate flux correlated with chloride flux (playa $r^2 = 0.76$; beach $r^2 = 0.88$; dune $r^2 = 0.96$), sodium flux (playa $r^2 = 0.78$; beach $r^2 = 0.86$; dune $r^2 = 0.81$) and potassium flux (playa $r^2 = 0.79$; beach $r^2 = 0.67$; dune not significant). Sulfate in dust was far higher than sulfate in the surface 5 cm of soil.

Levels of sodium were consistently high in playa dust and significantly higher than sodium in beach and dune dust (Fig. 6). From the beginning of the dust collection periods, dust concentration of sodium decreased at the beach and dune locations. Sodium concentration correlated with chloride concentration ($r^2 = 0.93$) for the playa and dune locations. The concentration of sodium in the surface soil was less than that in dust, but the magnitude difference was less compared to other measured solutes.
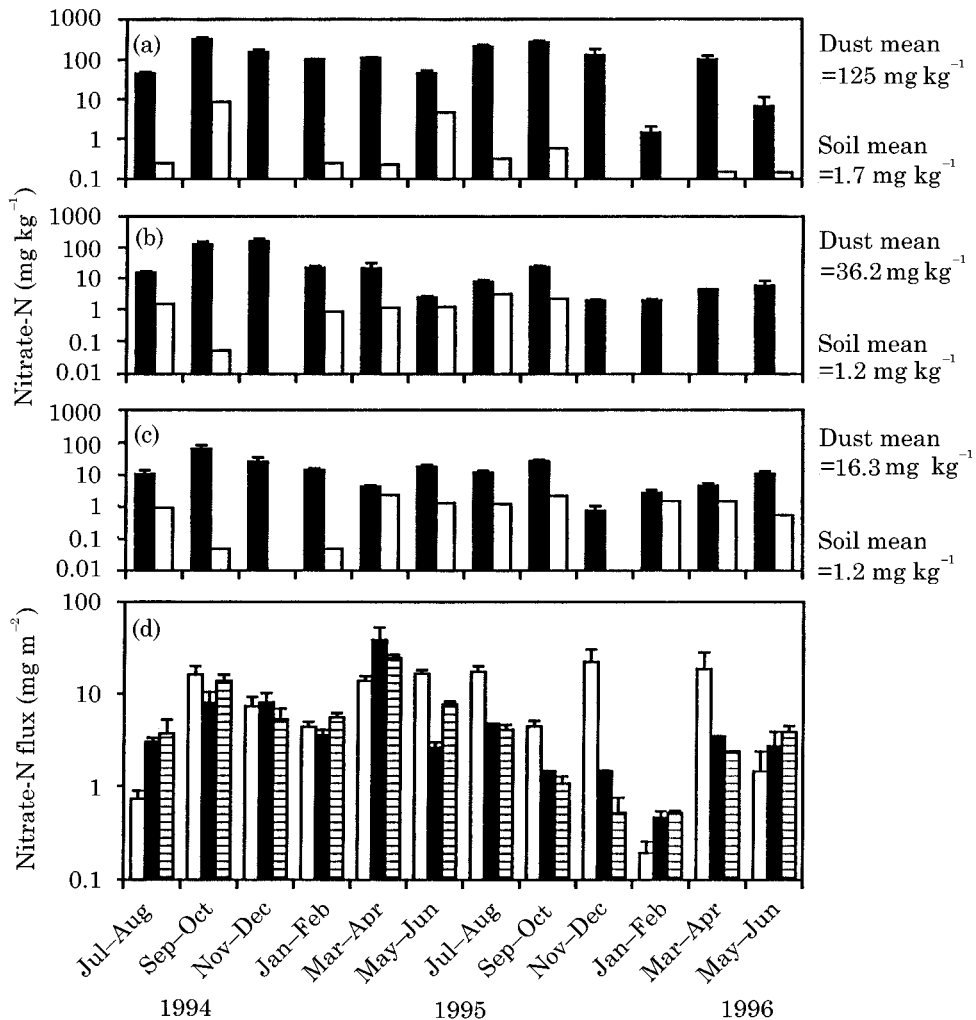
Figure 3. (a–c) Bimonthly aqueous-soluble nitrate-N concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Nitrate-N flux in the playa (□), beach (■), and dune (▤) locations. Cumulative yearly flux rates: playa = 1.6 kg ha^{-1} year^{-1}; beach = 1.1 kg ha^{-1} year^{-1}; dune = 1.1 kg ha^{-1} year^{-1}. ANOVA: concentration, location × time, $p < 0.0001$; flux, location, $p = 0.0041$ and time, $p < 0.0001$.

Sodium flux was significantly higher at the playa location. At all locations, sodium flux significantly correlated with chloride flux (playa $r^2 = 0.99$; beach $r^2 = 0.90$; dune $r^2 = 0.74$). Sodium flux also correlated significantly with potassium flux (playa $r^2 = 0.97$; beach $r^2 = 0.79$; dune $r^2 = 0.84$). Young & Evans (1986) reported sodium fluxes ranging from 4.5 g m^{-2} on a playa, to 0.6 g m^{-2} on the playa margin, to 0.009 g m^{-2} on a lower alluvial fan. Such high levels of sodium transport from playas to uplands has undoubtedly extended salt-desert plant communities during the Pleistocene (Young & Evans, 1986).

In general, playa dust had far more aqueous-soluble potassium than did beach and dune dust (Fig. 7). The highest levels of potassium occurred during the first three
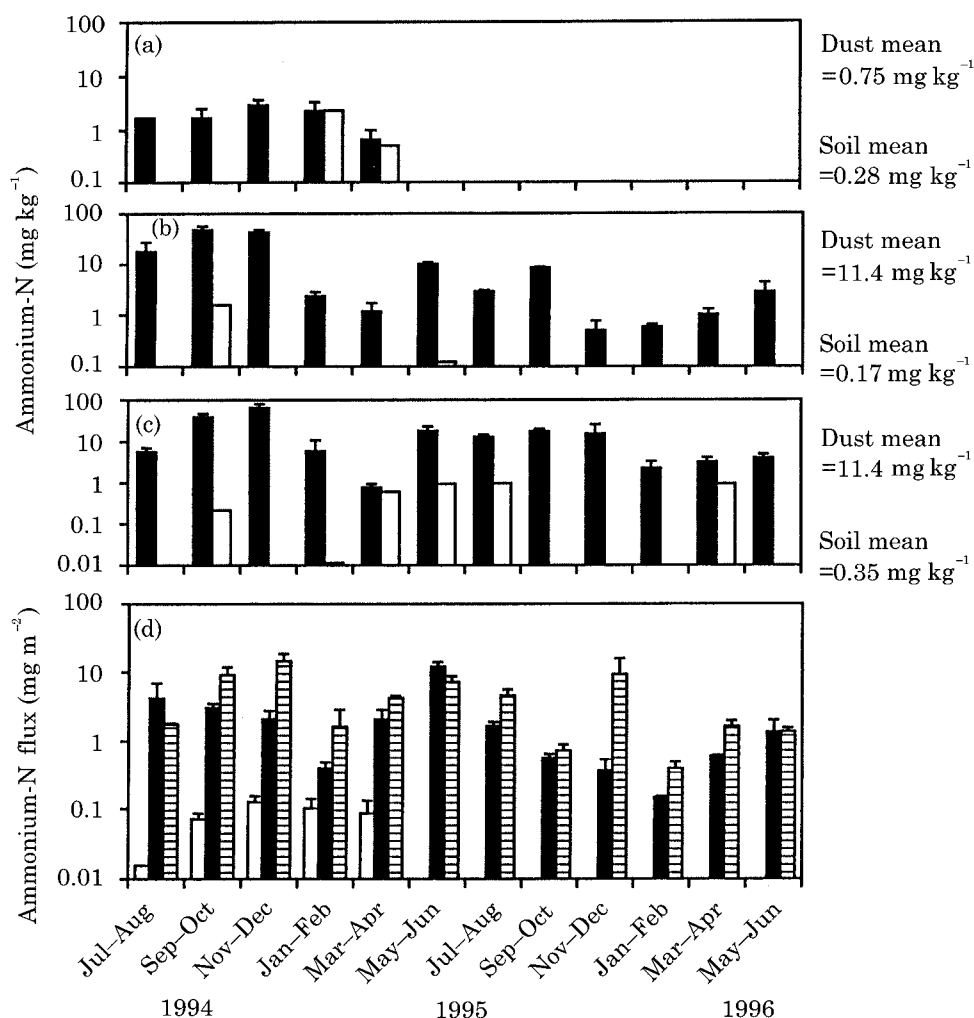
Figure 4. (a–c) Bimonthly aqueous-soluble ammonium-N concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Ammonium-N flux in the playa (□), beach (■), and dune (▤) locations. Cumulative yearly flux rate: playa = 0·006 kg ha^{-1} year^{-1}; beach = 0·41 kg ha^{-1} year^{-1}; dune = 0·85 kg ha^{-1} year^{-1}. ANOVA: location × time, $p < 0.0001$.

sampling times for the beach and dune locations, then significantly declined to nearly constant levels for the duration of the experiment. As for the previous solutes, levels of potassium in aeolian dust are generally far higher than that in the surface 5 cm of soil. At the playa site, potassium concentration significantly correlated with content of chloride ($r^2 = 0.95$), sulfate ($r^2 = 0.79$) and sodium ($r^2 = 0.97$). Of all the aqueous-soluble solutes studied, potassium has the greatest variability among replicates.

In general, boron content of dust declined from playa to dune locations (Fig. 8). Boron is unique in that it's dust and soil concentration for all locations and times is grossly similar. Over all locations, content of B has a high correlation with potassium ($r^2 = 0.96$), sodium ($r^2 = 0.92$), and sulfate ($r^2 = 0.83$). Aeolian dust emanating from this playa may have high B due to evaporative concentration from hot spring sources
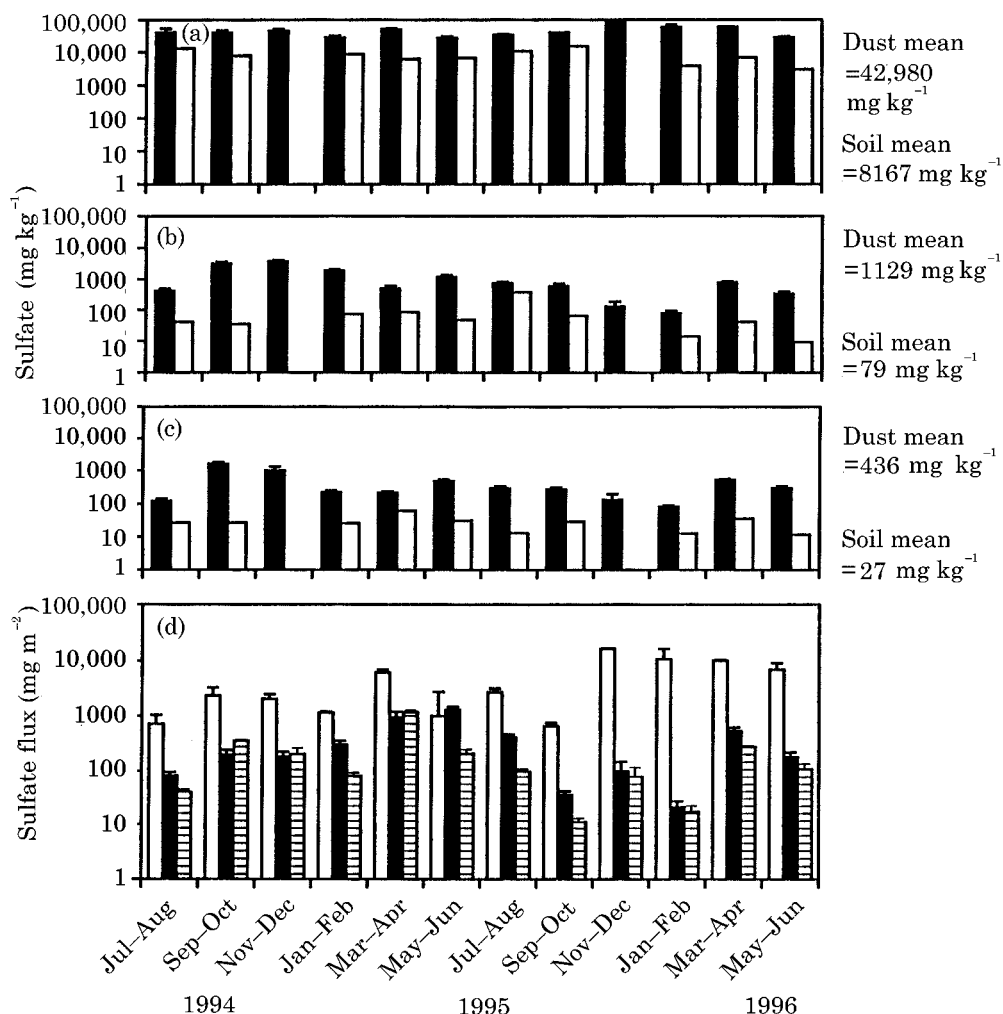
Figure 5. (a–c) Bimonthly aqueous-soluble sulfate concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Sulfate flux in the playa (□), beach (■), and dune (▤) locations. Cumulative yearly flux rate: playa = 920 kg ha^{-1} year^{-1}; beach = 66 kg ha^{-1} year^{-1}; dune = 40 kg ha^{-1} year^{-1}. ANOVA: location × time, $p < 0.0001$.

(Papke, 1976). Young & Evans (1986) reported a gradient of boron flux from 24 mg m^{-2} on a playa surface, to 6·0 mg m^{-2} on the playa margin, to 0·03 g m^{-2} on an alluvial fan. The high flux and high content in soil of such a phytotoxic element as B suggests a potential interaction with vegetation close to the playa.

HCl-extractable oxalate

Oxalate concentration in dust and oxalate dust flux was generally greatest in the beach and dune locations (Fig. 9). Concentration of oxalate and oxalate flux did not significantly correlate with any other measured solute concentration or flux. Soil concentrations of HCl-extractable oxalate were generally far lower than those in aeolian
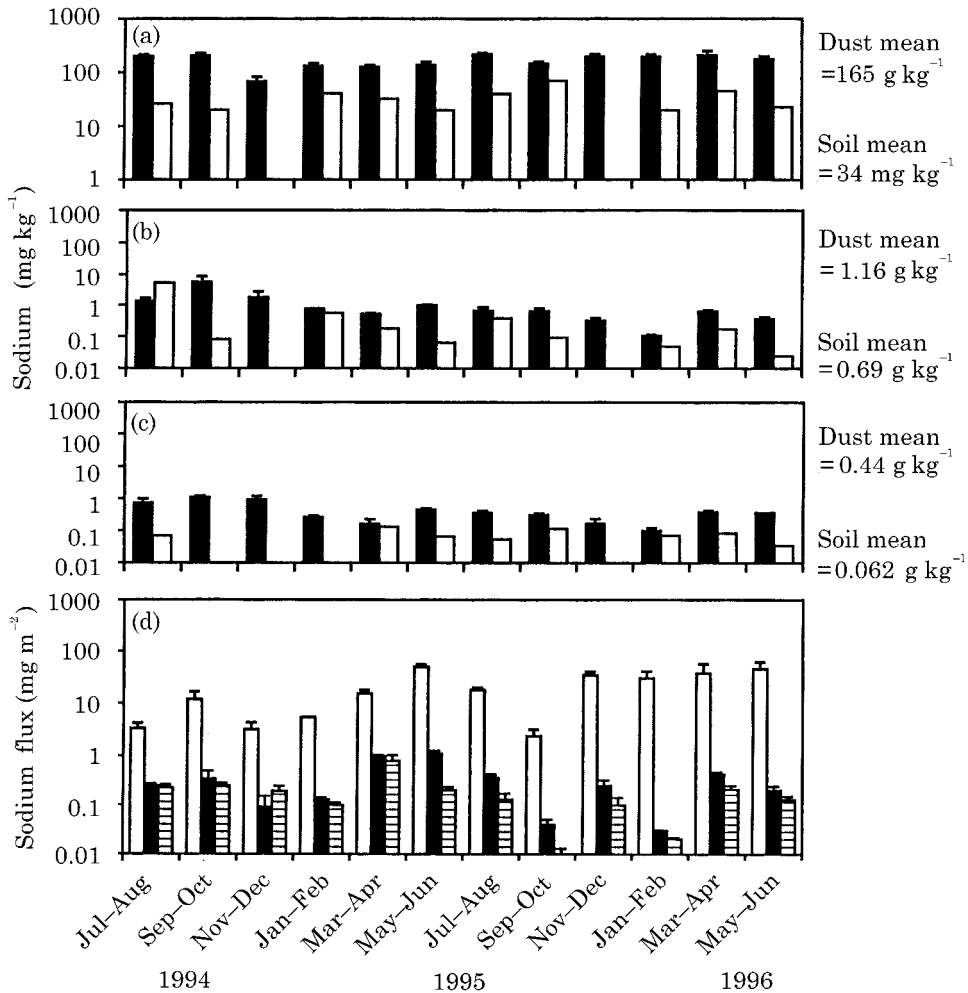
Figure 6. (a–c) Bimonthly aqueous-soluble sodium concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Sodium flux in the playa (□), beach (■), and dune (▤) locations. Cumulative yearly flux rate: playa = 3480 kg ha^{-1} year^{-1}; beach = 64 kg ha^{-1} year^{-1}; dune = 36 kg ha^{-1} year^{-1}. ANOVA: location × time, $p = 0.0003$.

dust. Some plants are known to synthesize oxalate as a cell osmoregulator (Egmond & Breteler, 1972). An average of 116 g kg^{-1} and 203 g kg^{-1} oxalate per dry weight was measured in leaf tissue sap of *Allenrolfea occidentalis* and *Sarcobatus vermiculatis*, respectively (unpublished data, ARS, Reno, Nevada). Given that oxalate levels in dust are lowest at the playa location with the least vegetative cover, and its low levels in surface soils, it appears that the oxalate in dust is from plant material. Although we removed large plant debris from our samples, undoubtedly there was contamination of the dust with minute plant parts. One potentially important aspect of oxalate in dust is the transport of its accompanying cation, which acid extractions indicate is largely calcium. Landscapes downwind from playa plant communities may receive considerable calcium via plant dust.
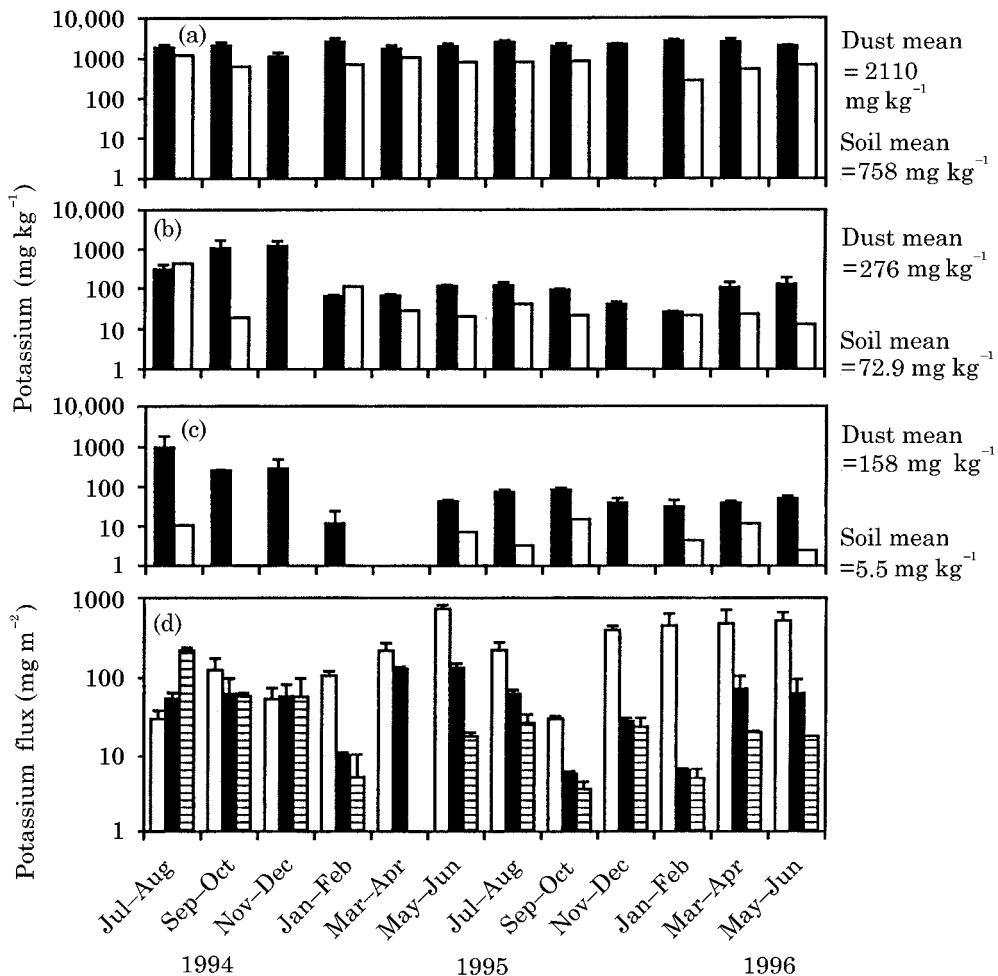
Figure 7. (a–c) Bimonthly aqueous-soluble potassium concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Potassium flux in the playa (□), beach (■), and dune (▤) locations. Cumulative yearly flux rate: playa = 46 kg ha^{-1} year^{-1}; beach = 11 kg ha^{-1} year^{-1}; dune = 7 kg ha^{-1} year^{-1}. ANOVA: concentration, time × location, $p = 0.034$; flux, time × location, $p < 0.0001$.

Aqueous-soluble solute content of aeolian dust and surface soil: why the disparity?

A perplexing result of our studies was that, in general, the aqueous-soluble concentration of a particular solute in aeolian dust greatly exceeded that of the same solute in soil. In this arid environment, given a constant dust flux rate for a particular element over a long period of time; wouldn't one expect similar average contents of the solute in dust and surface soil? Chemical species, such as the weakly sorbed anions nitrate and sulfate, could leach from the soil surface. If this were so, why does one of the most mobile anions, borate, have a similar content in aeolian dust and soil? Another cause of lower solute content in soil could be because of uptake by plants. In the short term, we reject this possibility because all samples were collected in unvegetated interspaces; there is no rooting activity near the soil surface in these microsites. Biologically active elements such
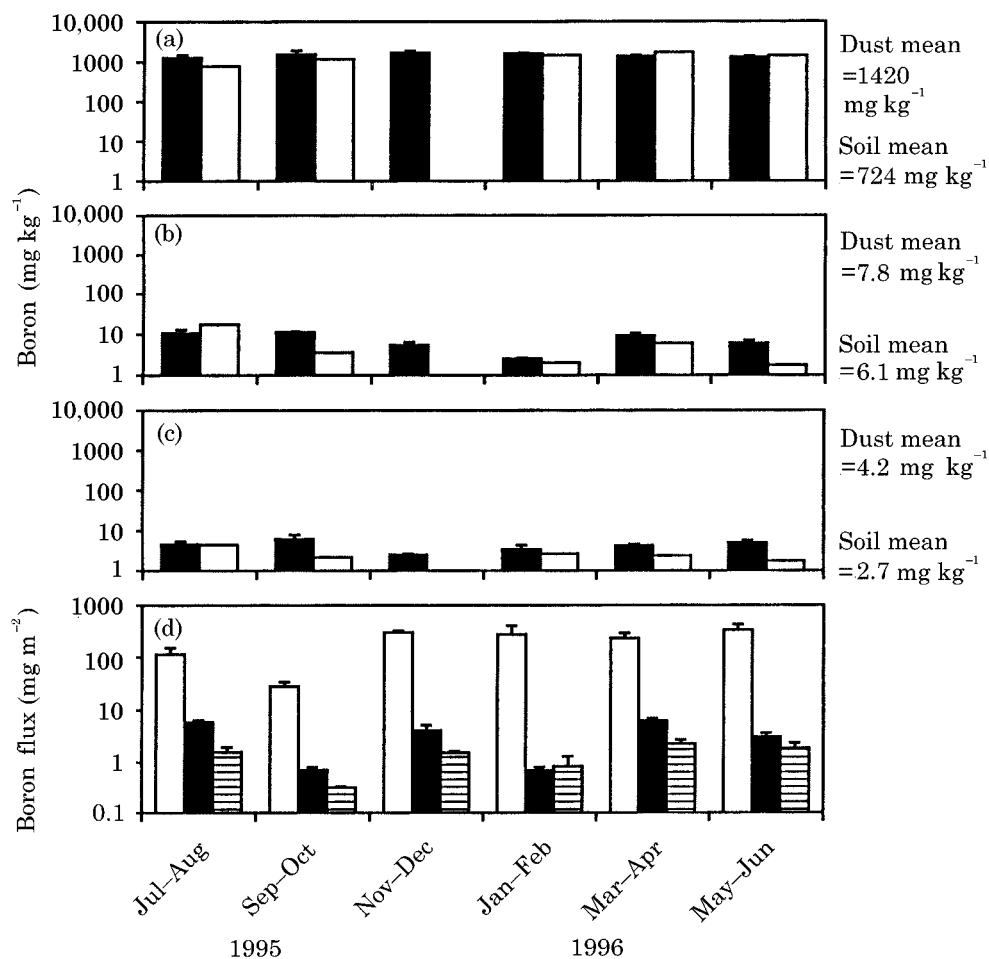
Figure 8. (a–c) Bimonthly aqueous-soluble boron concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Boron flux in the playa (□), beach (■), and dune (▤) locations. Cumulative yearly flux rate: playa = 1·80 kg ha^{-1} year^{-1}; beach = 0·03 kg ha^{-1} year^{-1}; dune = 0·01 kg ha^{-1} year^{-1}. ANOVA: time × location, $p = 0.0014$.

as ammonium and nitrate may experience gaseous losses through denitrification. Denitrification is a possibility at the playa site with its higher water content, but is unlikely on the very arid beach and dune soils with low organic carbon content. The cations potassium, sodium, calcium, and magnesium (data not presented in this paper for calcium and magnesium) are also far higher in aeolian dust than the soil surface.

One possibility for the differences in content of aqueous-soluble solutes between aeolian dust and soil is that dust infiltrates through the surface skeletal framework of sand deeper in the soil profile. To test this hypothesis, depth profiles of several aqueous-soluble solutes were obtained at each dust collector site (Fig. 10). These data indicate that, although levels of some aqueous-soluble solutes do increase with depth, even to 20 cm of soil depth for beach and dune sites, content of sulfate, potassium, and sodium is far less than occurs in dust at corresponding sites.
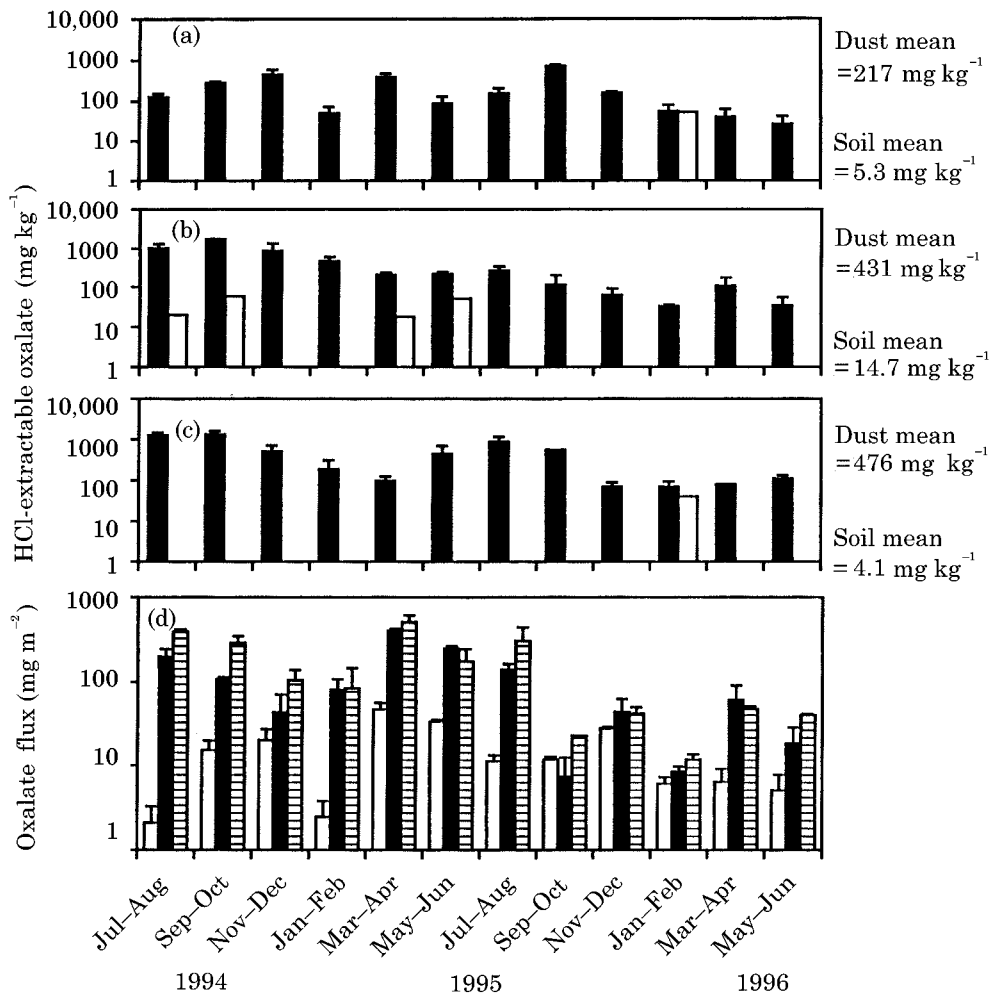
Figure 9. (a–c) Bimonthly HCl-extractable oxalate concentration (and standard error bars) in aeolian dust (■) and surface 5 cm of soil (□) in (a) playa, (b) beach, and (c) dune locations. (d) Oxalate flux in the playa (□), beach (■), and dune (▤)locations. Cumulative yearly flux rates: playa = 0·3 kg ha^{-1} year^{-1}; beach = 2·1 kg ha^{-1} year^{-1}; dune = 3·0 kg ha^{-1} year^{-1}. ANOVA: time × location, $p = 0.0014$. For concentration in dust and oxalate flux, there was a significant ($p = 0.0011$ and $p = 0.001$, respectively) month × location interaction (Fig. 8).

We hypothesize that the cause of greater solute content in dust as compared to the soil surface is that recent changes in playa hydrology has promulgated greater solute content in dust emanating from the playa. Neal & Motts (1967) provide evidence that most geomorphic features on playas in the western United States are less than 100-years-old and formed via climatic change and man's activities in de-watering via diversion or pumping. Gill (1996) reports that human diversion of water from Owens Valley, California greatly increases fugitive dust. Lowering of the playa water-table results in greater drying and cracking of the playa surface. Under these conditions, the playa surface is more subject to wind erosion with greater entrainment of salt efflorescences.
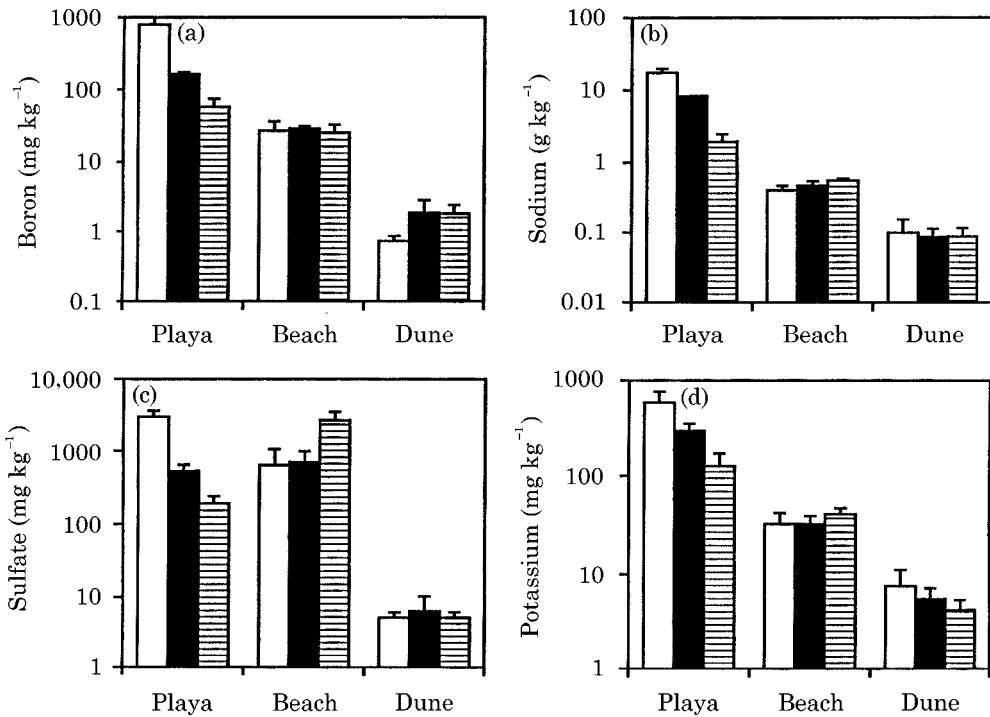
Figure 10. Aqueous-soluble soil solute content of (a) boron, (b) sodium, (c) sulfate, and (d) potassium by soil depth for the playa, beach, and dune sites. (□) = 0–5 cm; (■) = 5–10 cm; (▤) = 10–20 cm.

Aeolian dust nutrient deposition and weed invasion

Across the span of the Atlantic Ocean, aeolian dust from Saharan Africa provides nutrient elements to the Amazonian Basin (Swap *et al.*, 1992). It is reasonable to presume, then, that ecosystems downwind from saline playas might be impacted by elemental transfers. Extreme vegetational gradients near a salt playa in Utah are largely determined by soil salinity (Skougard & Brotherson, 1979). Wood & Sanford (1995) determined that aeolian deposition of salt downwind from a saline lake basin contributes such large amounts of solutes that subsurface water quality is degraded.

Given that salt transported by aeolian dust from playas influences vegetation, is there sufficient evidence from our study to support our working hypothesis; nutrient additions have triggered large-scale invasion of dune-mantled uplands by the weed *Salsola paulsenii* (barb-wire Russian thistle)? Nitrate is the major naturally occurring inorganic soil component which stimulates seed germination (Karssen & Hilhorst, 1992). Soil nitrate is known to stimulate the germination and invasiveness of weeds (Steinbauer & Grigsby, 1957; Popay & Roberts, 1970; Vincent & Roberts, 1977). The mechanisms involved in nitrate stimulation are complex and include interactions with light and temperature (Karssen & Hilhorst, 1992). Is the nitrate flux of $1 \cdot 1 \, \text{kg ha}^{-1}$ year^{-1} to the dune site in our study sufficient to have stimulated the invasiveness of *Salsola paulsenii*? Sufficient data are not available to predict a soil nitrate concentration that might stimulate the germination of *Salsola paulsenii.* Experiments by Hilhorst & Karssen (1988) have shown stimulation of germination in the range of

between 1 and 10 mM nitrate. In our study, there are periods when the concentration of nitrate in aeolian dust greatly exceeds this value, even though our measurements of nitrate in soil were generally far lower than 10 mM (Fig. 2). The evidence, then, is unclear. We suspect that timing is critical. Pulses of aeolian dust with high nitrate concentration, corresponding to a time when weed seeds are in a physiological state to be stimulated, could trigger a weed invasion.

There may be other factors involved in the invasion by *Salsola paulsenii.* The availability of soil nutrient resources is critical in the competitive stature of weeds (Radosevich & Holt, 1984). In the sandy substrates of the playa margin environment, high fluxes of essential nutrients such as sulfate and potassium via aeolian dust and precipitation may temporarily provide luxury levels for root uptake. Plants with rapid uptake kinetics and rapid growth strategies will be at a competitive advantage.

Conclusions

Over a 2-year period, we measured aqueous-soluble solute content of aeolian dust and solute fluxes bimonthly in a transect from a saline playa surface, to a remnant pluvial beach, to a dune-mantled upland. Concentrations of sodium, boron, sulfate, and potassium were highest in playa dust collection sites and decreased significantly towards the dune-mantled upland. Entrapment of solutes in the soil profile via wet and/or dry infiltration and dilution of solutes due to greater collection of saltating sand in dust traps in beach and dune sampling sites are two processes decreasing solute flux from the playa to dune-mantled upland. Seasonal and yearly variation in dust fluxes and solute content of dust in this environment is largely controlled by precipitation and wind patterns. Precipitation influences the proportion of the playa covered by water; greater coverage reduces salt entrainment. Strong northerly and north-westerly winds, typical in passing storm fronts, drive playa salts toward the uplands of the Hotsprings Mountains. Strong easterly and southerly winds entrain more sandy materials of the uplands and dilute solute content of dust emanating from the playa. The snapshot of aeolian dust patterns taken in this 2-year study does not likely gage the true variation in this ecosystem. Nonetheless, the fact that solute content of aeolian dust is far greater than occurs in the upper 20 cm of soil suggests that during the study period dust originating from the playa was transferring a greater amount of solutes to downwind uplands than the long-term average. If the fluxes of nutrients such as potassium, nitrate, ammonium, and sulfate and the content of salt in aeolian dust have recently increased due to changes in playa hydrology, one would expect an interaction with upland plant populations receiving appreciable aeolian dust additions. Increases in nutrient fluxes may be responsible for the invasion of high ecological condition dune-mantled areas by the weed *Salsola paulsenii.*

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